Naval Research Laboratory

Washington, DC 20375-5320 **NRL/PU/7104--93-239** **May 1993**

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Reprinted from 1993 *NRL Review*

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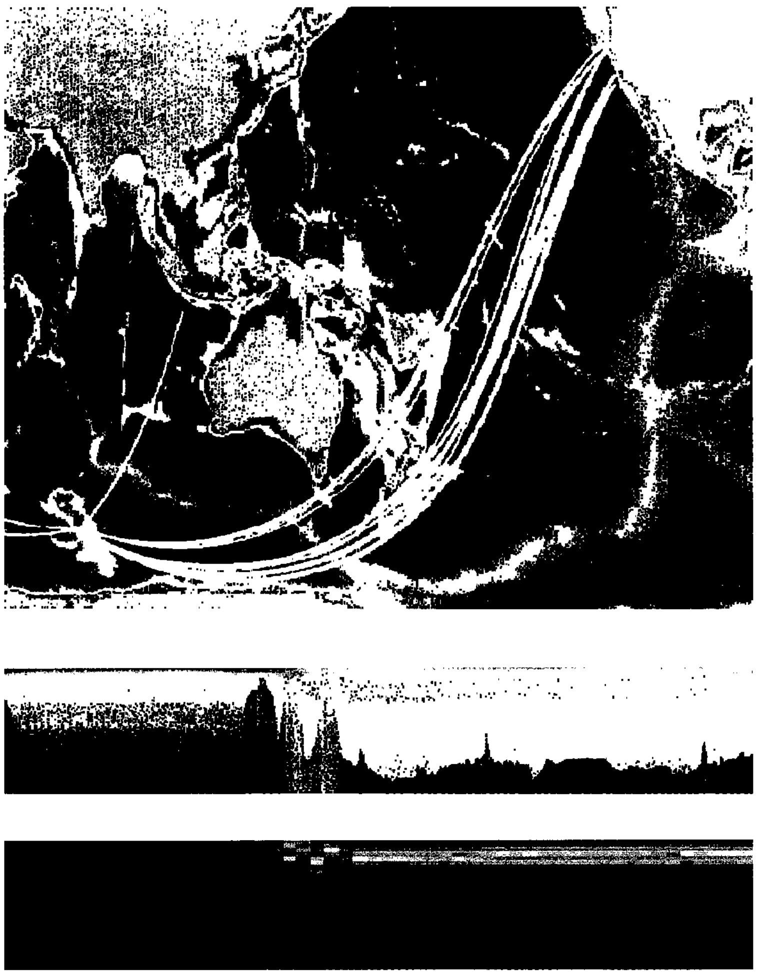

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INTRODUCTION

Can the world's oceans be used to monitor global warming? NRL is conducting theoretical/numerical investigations into the physics of ocean basin-scale acoustic transmissions to help answer this provocative question. If the coupled atmosphere/ocean system is warming at rates estimated from known greenhouse gas increases, sound travel times across major ocean basins may provide one of the most stable and accessible measures of major trends in global average temperature [1].

Acoustic Thermometry

The oceans contain a significant fraction of the ecosphere's heat content. It has been estimated that the oceans have absorbed about half of the heat content involved in temperature trends averaged over the past century. Measurements of sound propagation times across major ocean basins can provide temperature information averaged over large ocean volumes containing heat stored or lost during atmospheric temperature changes. The use of sound to measure temperature changes is referred to as acoustic thermometry. The Defense Advanced Research Projects Agency (DARPA) has recently initiated a multiyear program for Acoustic Thermometry of Ocean Climate (ATOC).

The sound speed of ocean water depends upon temperature, salinity, and pressure. Its most sensitive dependence is upon temperature, increasing on the order of 0.3%/° C warming. The measured atmospheric warming rate averaged over the past century is approximately 0.02° C/yr [2]. From this rate, modelers estimate a present warming rate 1 km below the ocean surface of roughly 0.005° C/yr [1]. Since measured sound transit times across the longest known ocean acoustic paths are roughly 10,000 s, the estimated present warming rate of the deep ocean should decrease the transit time by slightly more than 0.1 s/yr, a rate within the range of present measurement technology. Transit time measurements over a multiyear program may reveal whether the ocean is indeed warming at rates that might be of societal concern.

The Heard Island Feasibility Test

In January 1991, an ocean experiment of unparalleled interest and international cooperation was conducted from the vicinity of Heard Island in the Indian Ocean (Fig. 1). The Heard Island Feasibility Test (HIFT) was proposed and executed by Munk and colleagues [1] to establish whether sound from nonexplosive sources can be detected across major ocean basins and to provide a testbed for signal transmission algorithms. The location was chosen for its access to high-quality acoustic paths to both coasts of North America and other potential listening stations (some of which are illustrated in Fig. 1). A vertical array of ten sources operating near a center frequency of 57 Hz and generating approximately 100 kW total acoustic power was deployed near a mean depth of 175 m. A total of 18 installations consisting of oceanographic ships and/or hydrophone stations were donated by nine countries to listen for the signal in all major ocean basins except the Arctic. Cooperation with the experiment was

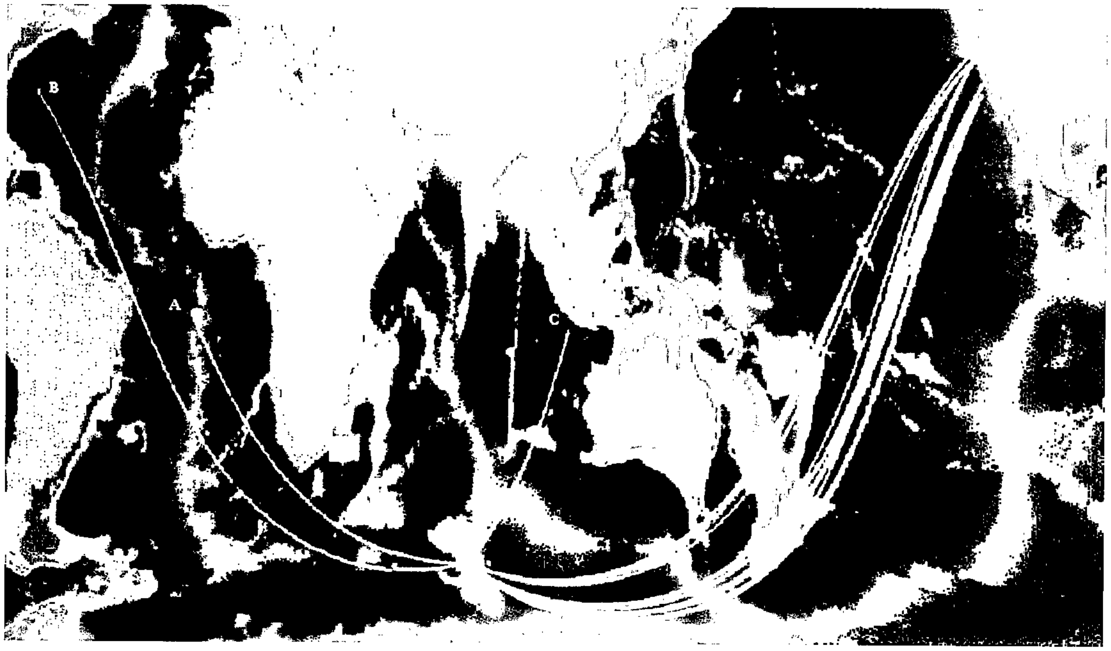

Fig. 1 — Calculated propagation paths from Heard Island to receivers at Ascension (A), Bermuda (B), Christmas (C), Oregon (D), and California (E). Each acoustic normal mode may in principle follow a different path: mode 1 is white, 2 is magenta, 3 is yellow, and 4 is red. Color scale for ocean depth: red is 0-200 m, yellow covers 1-2 km, and black is 6 km or more.

voluntary and without international organizational structure. Receptions of good to excellent quality were obtained at most stations. Adequacy of source levels was established, and timing accuracy had been established in earlier experiments as 0.001 s for a 1000 km path.

Why the Ocean?

The deep ocean has been known for decades to be a truly remarkable waveguide for long distance propagation of sound. The deep ocean sound speed as a function of depth typically reaches a minimum at a depth of roughly 1 km (Fig. 2). Proceeding down from the surface, the sound speed first decreases because of decreasing temperature. At great depth, temperature and composition parameters are roughly constant. The sound speed then begins to increase gradually downward because of increasing hydrostatic pressure. The roughly horizontal layer near the sound speed minimum is referred to as the ocean sound channel; the locus of the minimum is known as the axis of the sound channel. Snell's law for acoustic propagation in the deep ocean states that rays representing a propagating wave bend toward water of lower sound speed. A consequence of the existence of a vertical minimum in sound speed is that low grazing angle rays oscillate about the sound channel axis. Over long distances, they trace out approximately sinusoidal curves with wavelengths of order 50 km. Rays that oscillate about the axis without touching the surface or bottom are considered "trapped" in the sound channel.

Ray descriptions of wave propagation represent a high frequency approximation. To obtain a more accurate description of ocean acoustics at frequencies below roughly several hundred Hz, one deals with the continuous wave field of acoustic pressure oscillations. As with many cases of small amplitude oscillations in physics, it is helpful to resolve the acoustic pressure field into normal modes. Figure 2 shows the normal mode representation of trapped acoustic waves in the sound channel. These modes propagate horizontally in the sound channel, free of strongly dissipative interaction with the ocean surface or bottom. At low frequencies (e.g., 30-100 Hz), volume attenuation processes such as viscosity or molecular relaxation fall in the

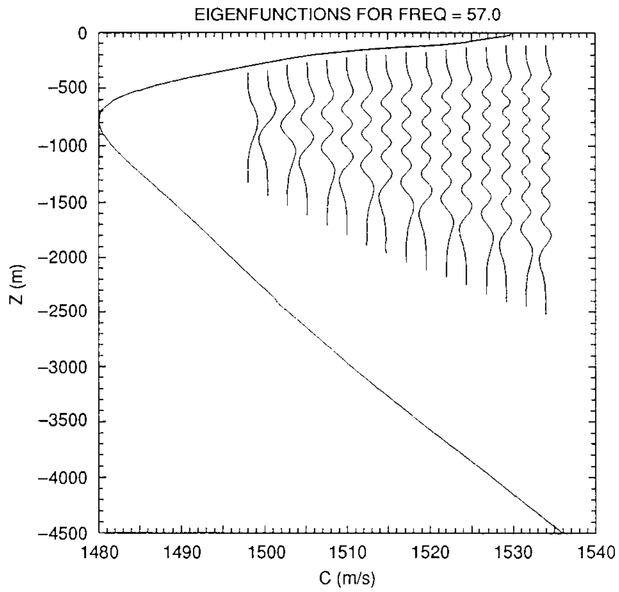

Fig. 2 — Normal modes of acoustic oscillation typical of the deep ocean. The sound speed profile $c(z)$ (left curve) was taken near Ascension Island in the South Atlantic (A in Fig. 1).

range of 10^{-4} to 10^{-3} dB/km. Signals in this frequency range have been received halfway around the world from their source, their amplitudes gradually decreasing as the inverse square root of distance (i.e., cylindrical rather than spherical spreading caused by the vertical constriction of the ocean waveguide).

Why not make measurements directly in the atmosphere? Atmospheric temperature records have been kept for over a century [2], but they are subject to major oscillations from weather systems and seasonal variation. Indeed, one has to average over decades just to begin assessment of a trend. Is acoustic thermometry over a large volume of atmosphere feasible? The atmosphere contains an acoustic waveguide caused by a vertical minimum in sound speed occurring in the stratosphere, and it exhibits an increase of sound speed with temperature comparable to that of the ocean. The atmosphere, however, is far too active, lossy, and plagued with natural and manmade noise to permit global scale sound transmission experiments to obtain volume-average temperature trends.

ACOUSTIC PROPAGATION PATHS

Two issues remain unanswered in the conceptual task of using ocean thermometry to monitor global warming: ambient variability and multipath in the received signal. The NRL work addresses the second. If two or more paths exist to the receiver because of reflection or refraction, establishment of travel times may be impeded by signal interference among the different paths. Understanding of detailed propagation paths may help in the choice of acoustic array location and/or interpretation of receptions.

The Perth-to-Bermuda Benchmark

An example of NRL's use of theoretical/numerical models to interpret experimental results is the 1960 acoustic propagation from a set of TNT charges detonated in the ocean near Perth, Australia. The experiment sought to detect the detonations with a set of hydrophones in the ocean near Bermuda, within 200 km of the antipode of the source location. The conceptual model used to locate the source and receiver was that of acoustic rays following great circles on a spherical Earth surface. All great circles through a given point meet exactly halfway around the globe. The convergence of rays on the antipode implies signal intensification; the signal should be of locally maximum amplitude near the antipode and hopefully detectable. Assuming sound propagation along great circles, there appeared to be an open water path between source and receiver (Fig. 3).

The experiment was an apparent success. Approximately 13,000 s after the detonation of

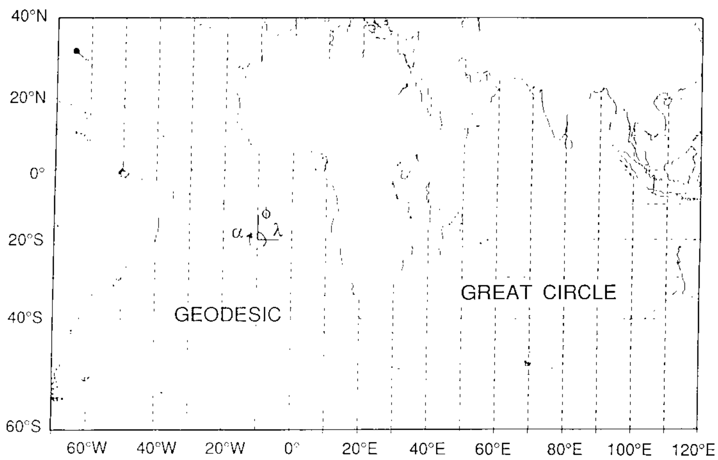

Fig. 3 — The great circle path from Perth to Bermuda compared to the geodesic (shortest distance path) on an ellipsoidal Earth as distorted by rotation. The large departures between great circle and geodesic result from the end points being very nearly antipodal.

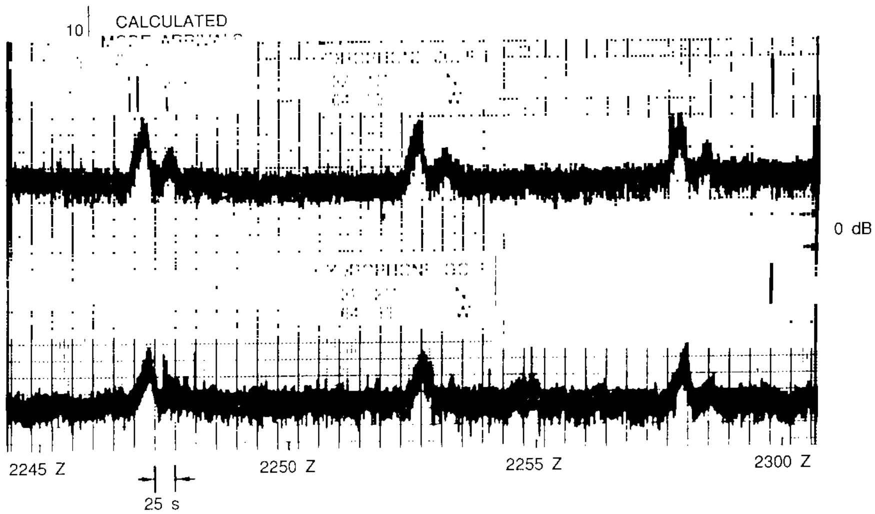

Fig. 4 — Strip chart from the 1960 Perth-Bermuda transmission. Approximately 13,000 s after the detonation of each 300-lb TNT charge, a pair of arrivals separated by approximately 30 s was recorded near Bermuda. The inset in the upper left gives the mode arrivals as calculated from the NRL adiabatic mode model.

each TNT charge near Perth, a pair of arrivals separated by approximately 30 s was recorded on the Bermuda receivers (Fig. 4). The double arrival structure had not been anticipated, but was conjectured to have resulted from an unidentified multipath. It was realized some years later that two important effects had been ignored in analyzing the 1960 experiment: (1) the distortion of the Earth's shape caused by rotation, and (2) the horizontal gradient in the ocean's acoustic index of refraction caused by the pole-to-equator temperature gradient. The importance of the Earth's nonsphericity can be seen in Fig. 3, which compares the great circle path from Perth to Bermuda to the corresponding geodesic on the ellipsoid that most closely represents the Earth as distorted by rotation (no refractive effects are included in Fig. 3). The geodesic path is considerably to the south of the great circle, but is apparently a clear water path. The attempt to correct for the refractive effect, however, was not greeted with apparent success.

In 1988, a refractive correction was computed [3] for the Perth-Bermuda path using the assumption that sound trapped in the sound channel propagates at the vertical minimum sound speed of the channel. This assumption allows a three-dimensional sound speed field c to be replaced with the two-dimensional field c_{min}, the minimum of c over depth. The 1988 work further simplified the calculation by assuming that c_{min} depends on latitude only, approximating the average north-south refractive gradient. The eigenrays (which connect source and receiver and satisfy a differential form of Snell's law in the intervening medium) calculated from these assumptions were displaced to the north and beached on the east coast of Africa, leaving the Bermuda receiver deep in a shadow zone. Considerable interest was stirred in explaining why the 1960 experiment worked. A global scale acoustic model should be able to explain Perth-Bermuda if it is to address comparable future experiments with success.

THE NRL EFFORT

The current NRL project in global acoustic propagation began in 1990 with an attempt to understand the negative result in the 1988 refraction calculation. It consists of two numerical/theoretical modeling areas: (a) adiabatic mode calculations for determination of acoustic normal modes, horizontal propagation paths of the modes, and times of flight and (b) newly emerging developments in parabolic equation (PE) methods for integrating outgoing wave fields in two dimensions—depth and range.

Adiabatic Normal Modes

We have used adiabatic mode theory to calculate horizontal phase speeds c_n ($n = 1, 2, \ldots$ being the mode number) as a function of latitude and longitude from existing ocean databases. From c_n and Snell's law, we find the horizontal path taken by mode n. The three-dimensional acoustic wave field may be represented as a sum over normal modes each possessing two-dimensional (horizontal) propagation characteristics. Adiabatic normal mode theory assumes that the ocean waveguide varies so slowly in the horizontal that energy in mode n at any given location remains totally in mode n as the signal propagates through the waveguide. Calculation of the vertical normal modes yields the horizontal phase speed for each mode, including dependencies on ocean and bathymetric parameters. In general, modal phase speeds increase toward shallow water. A result of this dependency in light of Snell's law is that sound rays tend to veer away from bathymetric features and toward deeper water.

Upon numerical integration of the horizontal ray equations derivable from adiabatic normal mode theory [4], we found that each of the first several modes possesses multiple eigenray solutions for the Perth-to-Bermuda path. Figure 5 illustrates the five eigenrays found for mode 1 and six for mode 2. Northern and southern eigenray bundles (denoted A and B) result from blockage of the intervening region by Kerguellen Banks (near 70° E longitude). Micromultipath within bundles A and B results from grazing bathymetric reflections in regions denoted by rectangles. Integration of group travel times along the modal propagation paths yielded good agreement (Fig. 4) with the experimental data, including the double arrivals.

Even though the experimental data are 30 years old, the NRL work since 1990 has produced the following unexpected but quantitatively sound interpretation of the Perth-Bermuda results: The first of each double arrival is a signal along the shorter and faster path A, with the second being along the longer and slower path B. (By faster, we mean that the average sound speed is higher. This is a result of the waters along path A being warmer than those along path B.) The pulse widths at the receivers are consistent with the calculated levels of dispersion in the ocean waveguide along the propagation paths.

The PE Method

The PE method, which accounts for coupling of energy between modes, involves approximating the full wave equation with a

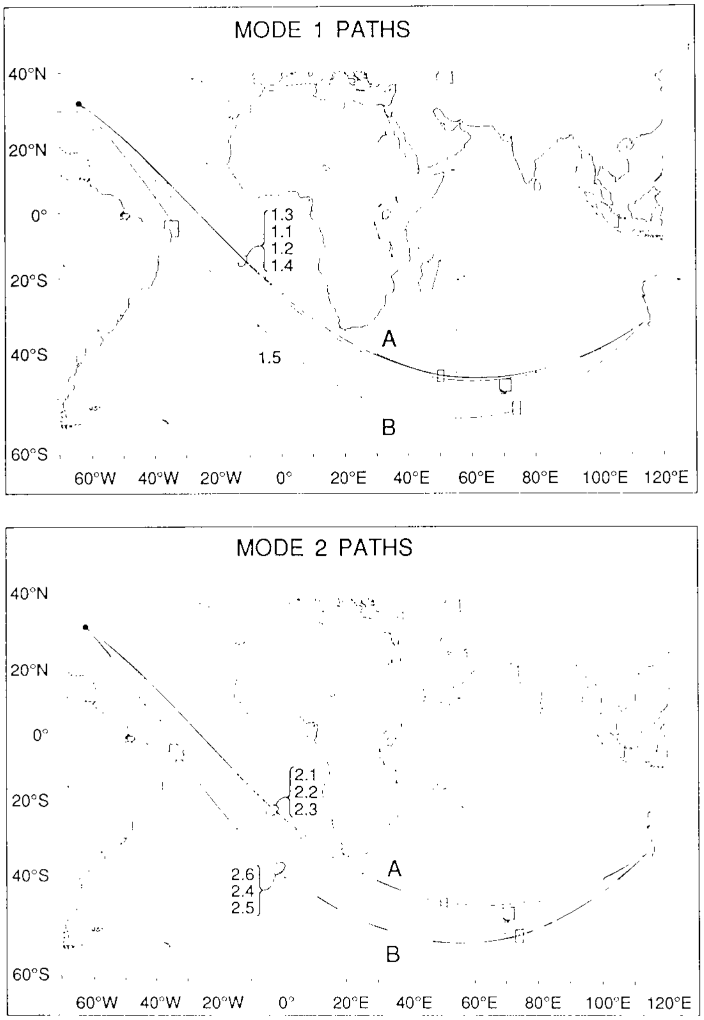

Fig. 5 — Modal eigenrays for the Perth-Bermuda experiment as calculated by the NRL model

one-way wave equation that may be solved efficiently. The PE method is accurate because its assumptions about how sound propagates are generally applicable to the ocean: energy is mostly outgoing, and the speed of sound varies gradually in the horizontal directions. Until recently, PE solutions were obtained with the following two-step procedure: (1) apply a Padé approximation (which is more accurate than a Taylor series) to derive a one-way wave equation and (2) apply standard numerical techniques to solve the one-way wave equation.

It is possible to combine these steps so that the robustness of the Padé approximation is exploited to reduce both asymptotic and numerical errors [5]. A PE model based on this approach is about two orders of magnitude faster than contemporary PE models with similar capability. Once the horizontal propagation paths are determined, this PE model is used to solve for the outgoing wave field in the two-dimensional space defined by depth and horizontal range along the propagation path. Since the new PE model permits very large steps in the range integration, it is practical to consider all of the major HIFT propagation paths.

THE HEARD ISLAND RESULTS

Several features of the 1991 HIFT data are in excellent agreement with expectations. Many of the listening stations received clear signals;

most arrival angles were in close agreement with the NRL model's calculated eigenrays [6]. Launch angles for the eigenrays (inferred experimentally from Doppler shifts at the receivers) were also in general agreement with eigenray calculations. At Christmas Island, the received signal contained a Doppler shift that was used to infer source motion along the line of sight. The source ship's motion recorded via satellite agreed with the Doppler-inferred position within 10 m over the course of one hour's transmissions.

There were, however, some surprises. Some of these remain unresolved, but some have found interpretation via the NRL model. A vertical array off California detected approximately eight modes surviving the nearly 18,000 km flight from Heard Island. It had been expected that bathymetric interaction near New Zealand would strip off modes higher than the first few, since shallow coastal seafloors absorb energy preferentially from high modes.

Another surprise was the complexity of the signal received at Christmas Island. The propagation path from Heard to Christmas was primarily south-to-north, so that the signal spent minimal time in the dispersive conditions near the Antarctic Circumpolar Convergence. A synthesized 0.1-s pulse transmitted from Heard had spread to over 5-s width in 5,500 km propagation to Christmas. Despite the phase stability implied by the accuracy of the received Doppler shift, the signal amplitude structure within the 5-s pulse width changed markedly during transmissions repeated at 45-s intervals.

The NRL Predictions

Figure 1 shows modal propagation paths from Heard Island to major receiving stations, as computed by the NRL adiabatic mode model. For most of the paths, results for travel time and signal bearing at the receiver agreed with experimental data. The paths through the Tasman Sea (between Australia and New Zealand), however, were apparently blocked or subject to strong absorption. A Japanese team near Samoa failed to receive signals along this path. As determined from signal travel time and bearing at the receiver, a hydrophone installation off the coast of Oregon received the signals passing south of New Zealand, but the ones through the Tasman Sea were not detected.

Figure 6 gives the NRL model interpretation of the signals received at a vertical array off San Diego. Figure 6(a), gives the propagation path for mode 1. In Fig. 6(b) we give a depth-range PE calculation of the sound intensity along the mode 1 path. The calculation is initialized near Heard with a point source at 175 m depth. In Fig. 6(b), one sees evidence of bottom loss from Heard to the southernmost point (B) of the ray path and then on the shoulders (C) of the New Zealand plateau. Many modes are present at zero range as a result of point source excitation. One sees rather modest exchange of energy between modes until just before the New Zealand plateau (C). Just before the shallowest water along the path, Fig. 6(c) reveals that modes higher than about 9 suddenly disappear. Figure 6(b) at this point indicates the sudden presence of deeply penetrating sound in the bottom, i.e., mode dumping. Past the New Zealand plateau, there is only modest modal redistribution. When the ray reaches California, the first eight modes are well populated. This result is consistent with the vertical array's unexpected reception of roughly eight modes off California. The NRL model attributes the origin of these modes to bathymetric interaction south of New Zealand.

One of the HIFT exercises demonstrated "pulse compression" by transmitting different frequency components of a short pulse in different time windows. The frequency components were later combined in a common time window during signal processing. The simulated wavetrain consisted of five cycles of a 57 Hz sine wave, for a total pulse length of approximately 0.09 s.

The various frequency components of the pulse were transmitted with coded phase shifts for identification purposes. After propagating a distance of 5,500 km (Heard to Christmas Island), the signal components were recorded and later superimposed numerically. The synthesized pulse revealed unexpected multiple arrivals with an envelope of width approximately 5 s (Fig. 7). On the Heard-Ascension Island leg (9000 km, result not shown here), the pulse

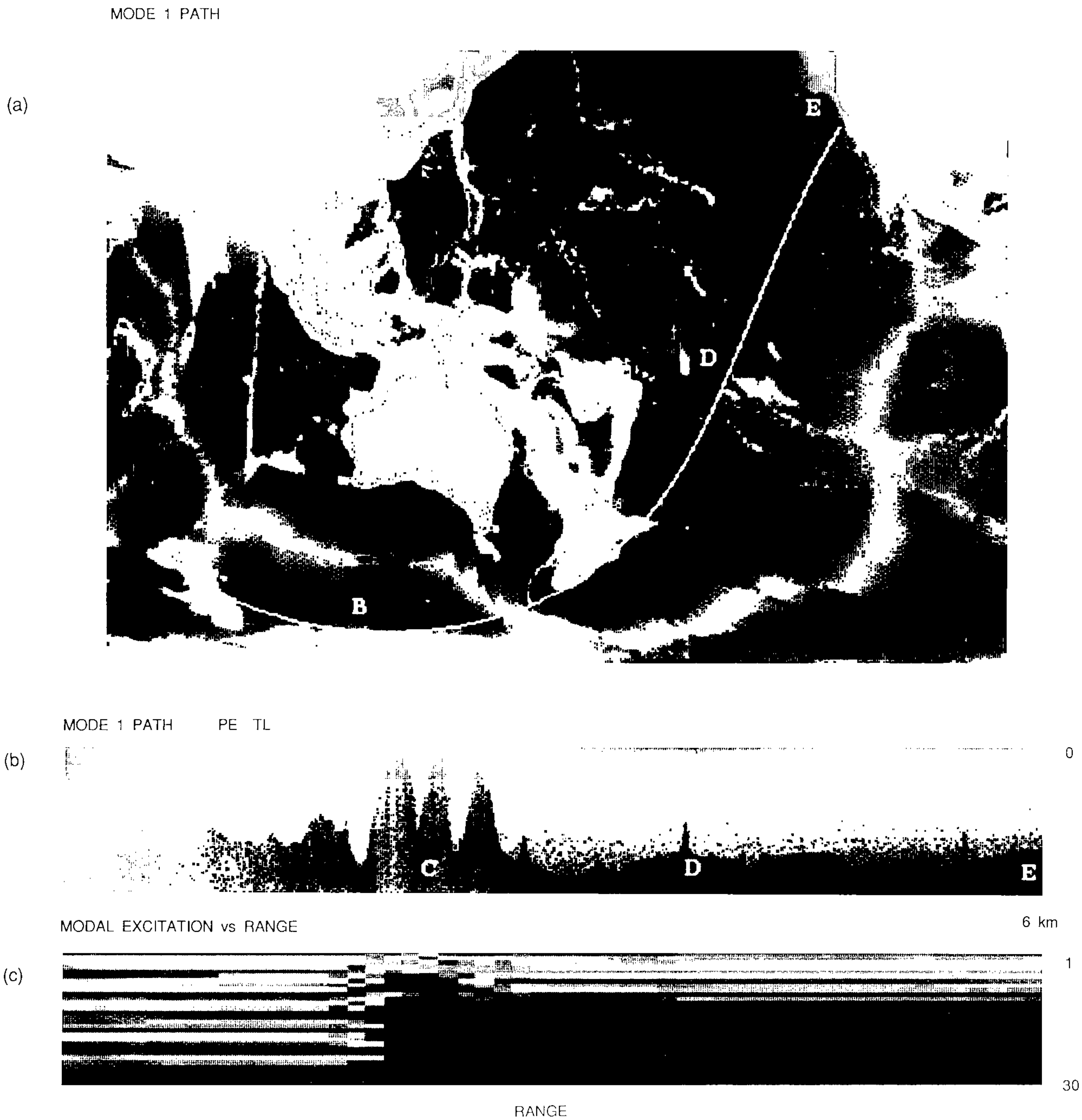

Fig. 6 — Depth-range PE calculation from Heard Island to the array off San Diego for a point source at 175 m depth. (a) The ray path used is that for mode 1 at 57 Hz, (b) acoustic intensity and bathymetry along the ray, and (c) modal excitation levels along the path for modes 1 to 30. The vertical extent of Fig. 6(c) is divided into 30 strips for modes 1 to 30. The maximum mode amplitude at any given range is represented by red and the minimum by black.

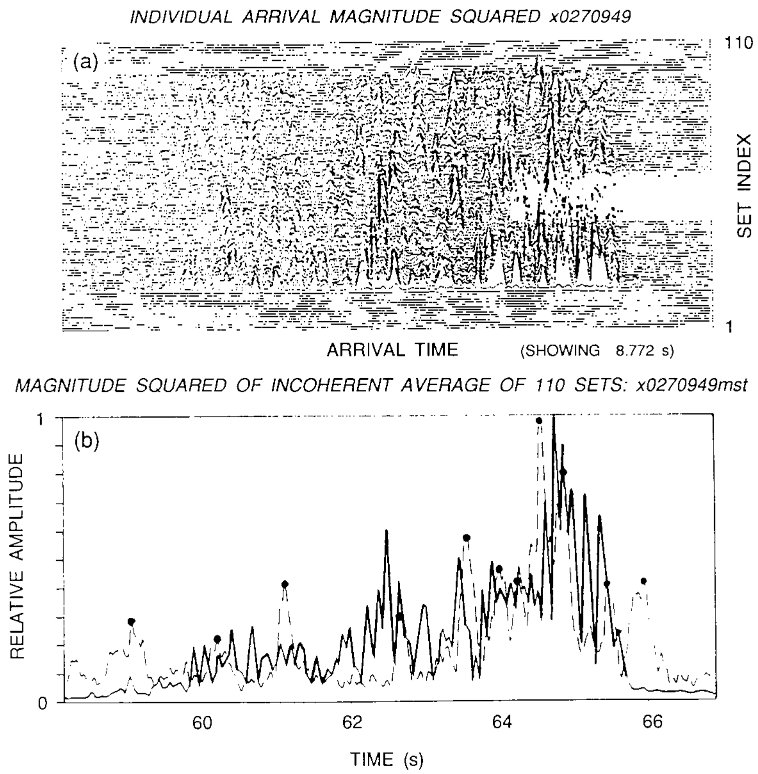

Fig. 7 — (a) Pulse-compressed transmissions as received at Christmas Island, 27 January 1991. The transmissions were repeated at 45-s intervals; and (b) solid line is average intensity for (a). Dashed line with dots denoting maxima: NRL Heard-to-Christmas Island pulse calculation. (Figure courtesy of K. Metzger, University of Michigan.)

width had spread to roughly 7 s. Different transmissions of the same pulse along the same path resulted in different microstructure in the reconstructed pulse, but the length of the synthesized pulse train was fairly consistent from transmission to transmission.

In Fig. 7, we give model calculations and experimental results for time domain pulse transmission from Heard to Christmas Island. Our numerical Heard-to-Christmas pulse transmission was carried out using mode theory with coupling terms to account for the exchange of energy between modes during interaction with bathymetry. We are in the process of repeating the pulse transmission calculation with the PE for comparison. The calculation illustrated in Fig. 7 excited 30 vertical modes appropriate to point source excitation at 175 m depth. For each mode, coupled mode calculations were performed for 21 equally spaced frequencies between 52 and 62 Hz. Resulting modal phase speeds were interpolated to a fine set of 512 frequencies and used to synthesize a pulse consisting of five cycles of a 57 Hz sine wave. All integrations were carried out on the 57 Hz mode 1 path. Although this compromises the separate identity of modal paths, it should be a good approximation. Fermat's principle states that along eigenrays, the path integrated phases are stationary with respect to ray displacement.

While microstructure in the results shown in Fig. 7 differs considerably from that of the experiment, the temporal spread and shape of the pulse envelope is fairly reasonable. One should not even hope for detailed agreement with observed microstructure since it changed with each pulse transmission. The approximate agreement in wavetrain envelope indicates that our calculated modes are subject to approximately the right levels of dispersion (i.e., differences in group velocity). In any event, our calculation appears to capture complex arrival structures not anticipated by experimentalists for this path.

SUMMARY

The NRL global-scale acoustic propagation models are being used in support of an experimental effort to monitor global warming. These models have yielded new interpretations of global-scale ocean acoustic propagation data, suggesting that horizontal multipath must be taken into account when designing global-scale acoustic networks and analyzing data. The NRL models are currently being used to analyze the results of the Heard Island Feasibility Test. The capability represented by the NRL models will contribute to a multiyear DARPA program, Acoustic Thermometry of the Ocean Climate (ATOC). The goals of ATOC are to monitor temperature trends in the deep ocean as one means of detecting global warming.

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THE AUTHORS

B. EDWARD McDONALD received degrees in physics from Utah State University (B.A., 1966) and Princeton (M.S., 1968; Ph.D., 1970) after which he joined the NRL Plasma Physics Division in 1970. He has published in the fields of solar physics, fluid dynamics, plasma physics, numerical analysis, oceanography, and ocean acoustics. From 1970 to 1980 he carried out numerical investigations of ionospheric plasma processes related to high altitude nuclear weapons effects and to naturally occurring plasma turbulence affecting satellite communication. From 1980 to 1990 he worked for the Naval Ocean R&D Activity/Naval Oceanographic and Atmospheric Research Laboratory developing theory and numerical solution techniques for fluid dynamics and nonlinear acoustics. He joined the NRL Acoustics Division in 1990. Since that time he has developed theory and computer models for prediction and interpretation of ocean experiments in the following areas: sonar echoes from the sea surface under wind conditions, underwater acoustic propagation across major ocean basins, and acoustic thermometry of the ocean climate. The latter area is an ongoing effort to use acoustic properties of the oceans to monitor global warming trends. McDonald holds NRL Publication Awards (1975 and 1980), a number of performance awards, Division and Directorate Best Product Awards (1989), and is a Fellow of the Acoustical Society of America.

WILLIAM A. KUPERMAN received degrees in physics from Polytechnic Institute of Brooklyn (B.S., 1965), the University of Chicago (M.S., 1966) and the University of Maryland (Ph.D., 1972). He joined the NRL Acoustics Division in 1967. Beginning in 1976, he spent five years at the SACLANT Undersea Research Centre in La Spezia, Italy, where he founded the Environmental Modeling Group. He returned to head the Numerical Modeling Division at what is now the Stennis Space Center. In 1985 he returned to Washington, DC, and became the Senior Scientist of the Acoustics Division. He has done theoretical and experimental research and has, over the years, spent about one year at sea. He has conducted research and published papers on linear and nonlinear propagation, scattering, ambient noise, geophysical inverse theory, signal processing, and nonlinear optimization using simulated annealing. Among his present activities, he is the senior scientist of a multicountry, multiship set of experiments to be conducted in the Tasman Sea investigating the use of the ocean environment to enhance signal processing. Dr. Kuperman was elected a Fellow of the Acoustical Society of America in 1980 and is an associate editor of the *Journal of the Acoustical Society of America*.

MICHAEL D. COLLINS received degrees in mathematics from Massachusetts Institute of Technology (B.S., 1982), Stanford University (M.S., 1986), and Northwestern University (Ph.D., 1988). Dr. Collins was a Volkswagen mechanic prior to being hired in 1985 by the Naval Ocean Research and Development Activity (now NRL-Stennis Space Center). Dr. Collins joined NRL in 1989 shortly after completing his thesis, which involved asymptotic and numerical methods for sound propagation and scattering in the ocean. His research at NRL involves modeling the propagation and scattering of acoustic and elastic waves, developing methods for solving signal processing and inverse problems, designing and performing at-sea experiments, and analyzing data. Problems he has investigated include localization of a source in a medium with unknown properties, time-domain beamforming by parameter optimization, inversion for ocean-bottom properties, and global-scale sound propagation in the ocean. Dr. Collins is a member of the Society for Industrial and Applied Mathematics (SIAM) and was among the youngest to be named a Fellow of the Acoustical Society of America (ASA) in 1990. From NRL, he received a Special Act Award in 1991 and an Alan Berman Research Publication Award in 1991, 1992, and 1993. He has been selected to receive the R. Bruce Lindsay Award from the ASA in 1993.

KEVIN D. HEANEY received degrees in physics from the University of California at Santa Barbara (B.S., 1987) and the University of Maryland (1990). While at the University of Maryland, he qualified for the Ph.D. program. His research was in the area of magnetic reconnection in solar and space plasma physics. He worked at Mission Research Corporation in Santa Barbara, California, and Newington, Virginia, during his undergraduate and graduate education. He did computational work in optical pattern recognition and electromagnetic particle simulations. After receiving his M.S. degree, Mr. Heaney joined Planning Systems, Incorporated as an on-site contractor at NRL in 1990. Since that time he has done analysis and computer simulation in the areas of acoustical oceanography, underwater acoustic propagation, scattering, nonlinear acoustics, and signal processing. Mr. Heaney developed the adiabatic normal-mode propagation code (RAYTRACE) used in the accompanying article. RAYTRACE is now being used by oceanographers and physicists at Scripps Institute of Oceanography at UCSD, CSIRO in Hobart, Tasmania, and SAIC in McLean, Virginia. Mr. Heaney's work has provided theoretical support for the Heard Island Feasibility Test and the upcoming ATOC experiments. His current research is in the area of broadband propagation through complex ocean environments and other aspects of acoustic tomography.

Cover Photo

Top panel: Sound propagation paths from the Heard Island Feasibility Test site to various receiver stations as computed by NRL.

Middle panel: Intensity of sound in the ocean as a function of depth and range along the southernmost path. The signal interacts strongly with bathymetry southeast of New Zealand.

Lower panel: Illustration of modal structure evolution along the southernmost path. Modes 1 through 30 are represented by thin horizontal strips. In this example, mode 1 is selectively excited in the NRL model. Higher modes are generated by bathymetric interaction near New Zealand. Results are consistent with observations off California.